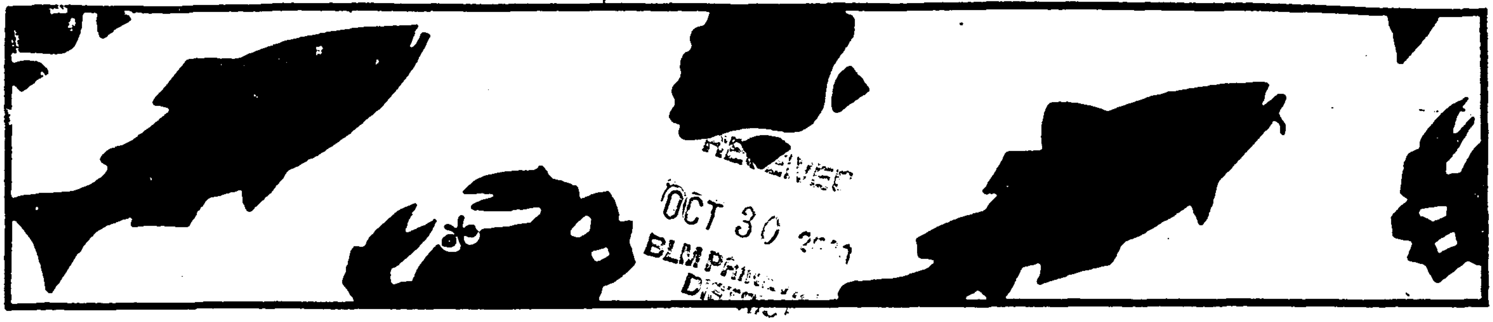
Kir Kendall



RECEIVED
OCT 30 20[illegible]
BLM PRINE[illegible]
DISTRICT

State of Washington

Vamer

State of Washington
DEPARTMENT OF FISHERIES

TECHNICAL REPORT NO. 119

HYDROPOWER FLOW FLUCTUATIONS AND SALMONIDS: A REVIEW OF THE BIOLOGICAL EFFECTS, MECHANICAL CAUSES, AND OPTIONS FOR MITIGATION

by
Mark A. Hunter
Fish Biologist
Habitat Management Division

Booth Gardner
Governor

September 1992

TECHNICAL REPORTS

The Technical Reports present results of completed or ongoing investigations carried out by the Department of Fisheries that are deemed of sufficient timely interest to be made available to the scientific community and the public.

The contents of these reports may be reprinted, and reference to the source will be appreciated.

STATE OF WASHINGTON
Booth Gardner, Governor

DEPARTMENT OF FISHERIES
Robert Turner, Acting Director

HABITAT MANAGEMENT DIVISION
Duane Phinney, Chief

P.O. Box 43135
Olympia, WA 98504-3135

Table of Contents

Page

1. Acknowledgements 1

2. Introduction 2

3. Unregulated and Regulated Rivers 3

4. The Biological Impacts of Flow Fluctuations 4

   a. Increases in Flow 4
   b. Stranding 5
   c. Juvenile Emigration (Salmonid Drift) 10
   d. Increased Predation 10
   e. Aquatic Invertebrates 10
   f. Redd Dewatering 12
   g. Spawning Interference 12

5. The Hydraulic Response to Flow Fluctuations 13

   a. Attenuation 13
   b. Lag Time 14

6. Types of Hydropower Activity That Fluctuate Flows or Otherwise Cause Stranding 14

   a. Peaking 16
   b. Low Flow Shutdowns 16
   c. Low Flow Start-ups 17
   d. Powerhouse Failures 17
   e. Intake Failures 18
   f. Cycling 18
   g. Multiple Turbine Operation 19
   h. Forebay Surges 19
   i. Reservoir Stranding 20
   j. Tailwater Maintenance and Repair Activities 20

Table of Contents (Continued)

Page

8. Field Methods 25

   a. A Word of Caution 25
   b. Estimation of Stranding Losses 25
   c. Ramping Rates Test 26

9. Discussion 26

   a. Flow Alterations and Flow Fluctuations 26
   b. Needs for Additional Research 28
   c. Does Stranding Only Occur in the Pacific Northwest? 28
   d. Resident Trout Stranding? 28

10. References Cited 31

List of Figures

Page

Figure 1. River Stages From Three Snoqualmie River USGS Gages April 4 to April 14, 1989 40

Figure 2. Hourly River Stage Recordings From Four Gages on Skagit River, March 19, 1982 41

Figure 3. River Stage Recordings From Six Sites Below the Snoqualmie Falls Second Powerhouse 42

Figure 4. River Stage Recordings from the Raging River Site and the Carnation USGS Gage on the Snoqualmie River 43

Figure 5. Flow Fluctuations at a Run-of-the-River Facility 44

Figure 6. Weeks Falls Turbine Flows During July 17 through July 21, 1988 45

Figure 7. Weeks Falls Turbine Flows During April 1989 46

List of Tables

		Page
Table 1.	Monthly tabulation of 11,771 measurements of hourly state for Youngs Creek, a tributary to the Skykomish River in Washington	35
Table 2.	Tabulation of 11,771 measurements of hourly stage changes by flow exceedence	36
Table 3.	Tabulation of 17,244 records of hourly river stage changes on the Sauk River (USGS #12189500) by flow exceedence percentiles	37
Table 4.	Tabulation of 17,244 records (including 118 no data records) of hourly changes in stage on the Skagit River at Marblemount (USGS #12181000) by flow exceedence percentiles	38
Table 5.	Ramping Range, Maximum Raping Rate, Ramp Duration, and Lag Time recorded from four gages on the Skagit River as a result of an experimental fluctuation event on March 19, 1982	39

Executive Summary

This technical report reviews the available research and evaluations on the effects of flow fluctuations on salmonids. It also summarizes how hydropower facilities create flow fluctuations, suggests criteria for mitigation, recommends field procedures, and identifies needs for further research. This technical report is limited to the review of flow fluctuations and does not address flow alterations.

Flow alterations are changes from the natural or unregulated flow that persist for weeks, months, or seasons, either as a result of water storage or as a result of bypassing a section of the river with a penstock. Flow alterations change the amount of habitat available to fish and, thus, change the capacity of the river to produce fish.

Flow fluctuations are unnatural changes in flow over periods of minutes, hours, or days. The biological impacts include immediate mortality, delayed mortality, temporary loss of habitat, reduced reproductive success, loss of food resources, and behavioral responses that could reduce survival or growth. The effects of flow fluctuations are not well-understood by many biologists outside the Pacific Northwest involved in hydropower mitigation, and many site-specific investigations completely ignore the impact of flow fluctuations.

The physical hydraulics of unregulated (i.e., natural) and regulated (i.e., hydropower controlled) rivers are compared to emphasize that unregulated rivers rarely experience drops in stage (i.e., water surface elevation) in excess of two inches per hour, except during floods, whereas regulated rivers may experience a much higher frequency at low and medium flows. Thus, aquatic life forms are not necessarily adapted to stage drops in excess of one or two inches per hour.

The most widely studied biological impact is stranding. Stranding has killed hundreds of thousands of juvenile salmon in single events. The incidence of stranding is affected by the life history stage of the fish, substrate type, river channel contour, range of flow change, rate of flow change, species, and time of day.

Other biological impacts have not been as thoroughly evaluated. These include redd dewatering, invertebrate productivity, fish emigration, and spawning interference. These impacts can be quite significant under some circumstances.

Hydropower facilities cause flow fluctuations in a variety of ways. Successful mitigation requires a thorough understanding of the operation practices and malfunctions that cause flow fluctuations. It is not sufficient to list criteria specifying allowable hydraulic changes. Developers often fail to recognize or acknowledge all sources of flow fluctuations, and when facilities are built that fail to address all potential sources of flow fluctuations, they will resist unanticipated and often costly alterations of their facilities or changes to their operation procedures. An overview of mechanical causes and suggested mechanical and hydraulic criteria are provided.

This report ends with a discussion on the significance of biological impacts relative to other types of hydropower impacts. The impact of flow fluctuations has been ignored in many site-specific evaluations and in most comprehensive reviews. Informational deficiencies and additional research needs are also discussed.

1. Acknowledgements

I should first acknowledge the efforts of the numerous individuals that performed the field work and reported their results in journals, technical reports, and hydropower license applications. Needless to say, this review would be impossible without such a foundation. Special thanks to Kevin Bauersfeld and Rod Woodin. These individuals performed some of the basic field research and provided encouragement and suggestions. Ross Fuller and Bob Gerke were also supportive and patiently reviewed multiple drafts of the report. Hal Beecher, Dawn Whitehead, Steve Fransen, and Stephanie Birchfield all provided external review of a preliminary draft. Phil Hilgerth, Carl Hadley, Al Solonski, and Tom Higgins provided key pieces of data or key ideas. Kurt Fresh and Linda Thunell assisted with polishing the document.

2. Introduction. This section defines the scope of this review.

Hydropower facilities can, to varying capacities, change instream flow patterns in rivers below the dams and powerhouses. These changes can be classified into two categories, flow alterations and flow fluctuations.

Flow alterations are changes in flow over long periods of time (weeks, months, or seasons) resulting from the storage of water, irrigation diversions, municipal diversions, or the reductions of flow between dams and powerhouses. These changes in net flow usually change the availability of fish habitat, and thus change the fish production potential of a river. Flow alterations are evaluated by studying the fish habitat requirements and estimating the changes in habitat area at different flows using a hydraulic model. The Instream Flow Incremental Methodology (IFIM) (Bovee 1982) has become a standard method for estimating habitat changes resulting from flow alterations. The IFIM methodology is routinely used to facilitate negotiation of instream flow requirements, usually minimum flow requirements, that meet the habitat needs of economically important or threatened fish species.

Flow fluctuations are unnaturally rapid changes in the flow over periods of minutes, hours, and days. Flow fluctuations can be immediately lethal or have indirect and delayed biological effects. This report reviews the **only** impacts of flow fluctuations on salmonids resulting from hydropower activity.

This report is divided into seven sections including:
(1) The difference between rivers regulated for hydropower and unregulated rivers; (2) The biological effects of flow fluctuations; (3) The hydraulic response of flow fluctuations over time and distance; (4) The types of hydropower activity that causes flow fluctuations; (5) Mitigation measures; (6) Field Methods; and (7) A concluding discussion. Anadromous salmonids (*Oncorhynchus spp.*) are emphasized, reflecting the available information on the subject. Most of the research and evaluation regarding the effects of flow fluctuations on salmonids has occurred in the states of Washington and Oregon. The discussion herein assumes the biological, geological, and hydrological

3. Unregulated and Regulated Rivers. This section describes the difference between unregulated and regulated rivers.

Flows in unregulated rivers respond to changes in precipitation and snow melt. West of the Cascade Range, the peak flows occur from heavy rain storms in November, December, and January. A lesser but more sustained peak occurs from a combination of rain and snow melt in the spring. The lowest flows coincide with the dry season that occurs in late summer and early fall. Glacial streams and streams on the east side of the Cascades have a somewhat different pattern. Here, the highest flows often occur in the spring and extend into the early summer. The lowest flows in some years occur during cold periods in the winter. In either case, periods of heavy rainfall or dry weather can create flows that are above or below seasonal averages. These natural flow variations indirectly affect fish production as a result of changes in the quantity and quality of instream habitat.

On a shorter time scale, individual storms can rapidly increase river stage in less than a day. After the storm, the stage declines to a relatively stable level over a longer period of time, usually days or weeks. In addition to storm events, limited daily stage changes sometimes occur during sunny weather as a result of snow melt run-off. Both types of natural flow changes are illustrated in Figure 1, which shows the hydrographs of three Snoqualmie River gages. This graph plots the river stage responses to a storm (April 4 through 8) and to snow melt (April 10 through 14).

Tabulation of hourly changes in stage provides insight on natural changes in flow. The first example is Youngs Creek, a medium sized stream located in the westside foothills of the Cascades. The hourly stage of Youngs Creek were recorded for a 15-month period, resulting in 11,771 observations of stage change (Table 1). Of these observations, there were 3182 records of no change, 3199 records of increases, and 5390 records of decreases. The number of decreases exceed increases because increases are typically greater in magnitude, and thus, it takes a greater number of decreases to offset the increases.

This data was tabulated by month and flow exceedence ten-percentiles. The most severe fluctuations occurred in late fall and winter (Table 1) and most stable flow occurred during the August and September dry season. As might be

In a second example, hourly stage changes in adjacent regulated and unregulated rivers were tabulated for comparison. The Sauk River and upper Skagit River (Marblemount gage) are rivers of similar size. Both rivers originate from the North Cascades mountains. The Sauk River is unregulated, and the upper Skagit River is regulated by three dams. The discharge from the lowest dam is subjected to daily flow fluctuations during parts of the year as a result of changes in demand for electric power (load following).

Nearly two years of data (October 1, 1989, to September 19, 1991; 17,244 observations) are tabulated for comparison. The distribution of flow fluctuations for the Sauk River (Table 3) is quite similar to that for Youngs Creek (Table 2). Only one record of decline in stage of 2 inches or greater occurred in the lower 90 percent of the flow range. Ninety-seven observations of declines in flow greater or equal to 2 inches per hour occurred in the highest 10 percent of the flow range.

By contrast, the Skagit River gage recorded 391 events of stage declines of greater than or equal to 2 inches per hour in the lower 90 percent of the estimated natural flow range, including four events in the lowest 10 percent of the natural flow range (Table 4). Despite significant moderation of discharge fluctuations at the lowest dam in recent years, the rate of change in the river flow is still highly unnatural.

In summary, rapid decreases in stage rarely occur in unregulated rivers, except during or immediately after floods. Thus riverine life forms are not necessarily adapted to survive such events. Landslides and rock falls can cause rapid flow decreases unrelated to floods, however, such events are rare and are unlikely to induce natural selection or learned behavioral responses in aquatic animals.

4. The Biological Impacts of Flow Fluctuations. This section describes all known biological impacts that result from flow fluctuations.

a. Increases in Flow

Evidence of biological impacts from rapid flow increases is scarce. Some impacts associated with rapid flow increases might be more appropriately associated with high flows. Rochester et al. (1984) noted that eggs and alevins can be killed when gravel scour occurs, and juvenile fish may be physically flushed down the river. Some species of aquatic insects that swim in pools can be physically flushed downstream from ...

salmonid population. Before and after index counts of juvenile salmonids were possible because an instream flow study was underway at the time. No significant difference in index counts could be determined (unpublished data, Chas Gowan, Harza NW, Bellevue, WA). However, indirect effects (i.e., aquatic invertebrates, long-term condition and survival of juvenile salmonids) were not assessed. It should be noted that the subsequent decline in flow did kill some fish.

The biological effects of unnatural flow increases are usually irrelevant in regulating hydropower operations because public safety concerns justify more stringent regulations than biological concerns. Flow increases can strand and occasionally drown fishermen and other people located on bars, rocks, or in confined canyons. Boaters might also be at risk under some circumstances. The remaining discussion in this review deals exclusively with the effects of decreases in flow.

b. Stranding

Stranding is the separation of fish from flowing surface water as a result of declining river stage. Stranding can occur during any drop in stage. It is not exclusively associated with complete or substantial dewatering of a river. Stranding can be classified into two categories: **Beaching** is when fish flounder out-of-water on the substrate. **Trapping** is the isolation of fish in pockets of water with no access to the free-flowing surface water. Stranding cannot always be neatly classified as beaching or trapping. Thus the text herein uses the term stranding unless a more specific term is appropriate.

Salmonid stranding associated with hydropower operations has been widely documented in Washington and Oregon (e.g., Thompson 1970; Witty and Thompson 1974; Phinney 1974, 1974b; Bauersfeld 1977, 1978; Becker et al., 1981; Fiscus 1977; Saiterwaite 1987; Olson 1990). Stranding can occur many miles downstream of the powerhouse (Phillips 1969; Woodin 1984). The estimated numbers of fish stranded in flow fluctuation events range from negligible to 120,000 fry (Phinney 1974). Stranding mortality is difficult or impossible to estimate (See Section 8.b.). Estimates are usually very conservative and/or highly variable.

Stranding can also occur as a result of other events, including natural declines in flow (author's obs), ship wash (Bauersfeld 1977), municipal water withdrawals, and irrigation withdrawals. Many factors affect the incidence of stranding. A recurrent theme in much of the following discussion is the high vulnerability of small salmonid fry.

i. **Life History Stage.** Juvenile salmonids are more vulnerable to stranding than adults. Salmonid fry that have just absorbed the yolk sac and have recently emerged from the gravel are by far the most vulnerable. They are poor swimmers and settle along shallow margins of rivers (Phinney 1974, Woodin 1984), where they seek refuge from currents and larger fish. Once chinook attain the size of 50 to 60 mm in length, vulnerability drops substantially. For steelhead, vulnerability drops significantly when the fry reach 40 mm (Beck Assoc. 1989). Larger juveniles are more inclined to inhabit pools, glides, overhanging banks, and midchannel substrates, where they are less vulnerable to stranding. However, many juveniles still inhabit shoreline areas, and remain vulnerable to stranding until they emigrate to saltwater (Chapman and Bjorn 1969, Hamilton and Buell 1976). Adult stranding as a result of hydropower fluctuations has been documented (Hamilton and Buell 1976).

ii. **River Channel Configuration.** The river channel configuration is a major factor in the incidence of stranding. A river channel with many side channels, potholes, and low gradient bars will have a much greater incidence of stranding than a river confined to a single channel with steep banks.

Large numbers of small fry die from beaching on **gravel bars** when unnatural flow fluctuations occur (Phillips 1969; Phinney 1974; Woodin 1984). Bauersfeld (1978) observed beaching primarily on bars with slopes less than 4 percent. Beck Assoc. (1989) determined that beaching occurred primarily on bars with slopes less than 5 percent. Under laboratory conditions, Monk (1989) determined that chinook fry stranded in significantly larger numbers on 1.8 percent slopes than on 5.1 percent slopes, however, results were not significant for steelhead. Stranding on steep gravel bars (>5 percent slope) has not been thoroughly studied.

Long side channels with intermittent flows are notorious for trapping juvenile fish. Substantial trapping can occur even with unregulated flows (Hunter, pers. obs.). Side channels are valuable rearing habitats, and juveniles of several species prefer side channels over the main channel. However, unnatural fluctuations will repeatedly trap fish, eventually killing some or all of them (Witty and Thompson 1974, Hamilton and Buell 1976, Woodin 1984, Olson 1990). Side channels can trap substantial numbers of fingerlings and smolts (up to 150 cm) as well as fry.

As water recedes from river margins, juvenile salmonids may become trapped in deep pools called **potholes** (Woodin 1984; Stokes and Jones Assoc. 1985). Potholes are formed at high flows from scouring around boulders and rootwads and where opposing flows meet. Potholes may remain watered for hours or months depending on depth of the pothole and the river stage. R.W. Beck Assoc. (1989) extensively studied pothole stranding in the Skagit River. Among the conclusions were: 1) Only a small fraction of the potholes in a river channel posed a threat to fish if fluctuations are limited in range; 2) The incidence of stranding is independent of the rate of stage decrease; and 3) The incidence of stranding was inversely related to the depth of water over the top of each pothole at the start of the decline in flow.

iii. Substrate Type. Most documented observations of stranding have occurred on gravel; however, stranding has also occurred in mud (Becker et al. 1981) and vegetation (Phillips 1969, Satterthwaite 1987).

Under laboratory conditions, Monk (1989) found significantly different rates of stranding on different types of gravel. In fact, substrate was statistically the most significant factor contributing to stranding of chinook and steelhead fry. On cobble substrate, fry (especially steelhead fry) were inclined to maintain a stationary position over the streambed (i.e., rheotaxis); while over small gravel, fry swam around, often in schools. When the water surface dropped, fry maintaining their position became trapped in pockets of water between cobbles, whereas mobile fish were more inclined to retreat with the water margin. When beaching became imminent, fry over cobble substrate retreated into inter-gravel cavities, where they became trapped. The difference in stranding rate was facilitated by the flow of water along a receding margin of the stream. On cobble substrate, the water drained into the substrate, whereas on finer substrates, a significant portion of the water flowed off on the surface.

iv. Species. Fry of some species are more vulnerable to stranding than others. In Washington State, stranding of chinook and steelhead fry have been frequently observed. Although pink salmon fry and chum salmon fry occur in the same rivers, they strand in lower numbers than chinook fry and steelhead fry (Woodin 1984). However, Beck Associates (1989) determined that the <u>rate</u> of chum and pink fry stranding per the available fry was substantially higher than for chinook. The low numbers of pink and chum salmon stranding is a result of the short fresh water residency; They emigrate to salt water shortly after emergence, whereas chinook and steelhead remain in the river for months or years.

Hamilton and Buell (1976) observed extensive coho stranding in the Campbell River (British Columbia) and coho stranding has been observed in incidental numbers in other studies (Woodin 1984, Olsen 1990). The overall incidence of coho stranding is rather low in the studies conducted to date. The likely reason for this is that coho prefer streams for spawning and rearing, whereas the formal research and evaluation has taken place in large and medium rivers. Juvenile coho rear for a full year in fresh water, and thus, it is reasonable to assume that stranding would occur at rates similar to chinook and steelhead.

Several episodes of sockeye salmon fry stranding have occurred in the Cedar River as a result of flow fluctuations (Fiscus 1977). Hvisten (1985) documents atlantic salmon and brown trout stranding in Norway.

v. **Ramping Range.** The ramping range or the total drop in stage from an episode of flow fluctuation affects the incidence of stranding by increasing the gravel bar area exposed. In addition, it increases the number of side channels and potholes that become isolated from surface flow (Beck Assoc. 1989).

vi. **Critical Flow.** Stranding increases dramatically when flow drops below a certain water level, defined as the **critical flow** (Thompson 1970, Phinney 1974, Bauersfeld 1978, Woodin 1984). In hydropower mitigation settlements, the critical flow is defined as the minimum operating discharge, or as an upper end of a flow range where more restrictive operation criteria are applied. The factors that likely account for this response have been discussed above. The exposure of the lowest gradient gravel bars often occurs in a limited range of flows. The exposure of spawning gravel from which fry are emerging may also account for the higher incidence of stranding.

vii. **Frequency of Flow Reductions.** In rivers with seasonal side channels and off-channel sloughs, even a natural flow reduction can trap fry and smolts. Under normal circumstances, the natural population can sustain a small loss several times a year. However, when a hydropower facility causes an repeated flow fluctuations, these small losses can accumulate to a very significant cumulative loss (Bauersfeld 1978).

Although many hydropower mitigation settlements specify ramping rates, some research has indicated that ramping rates cannot always protect fish from stranding. Woodin (1984) determined that any daytime ramping stranded chinook fry. Beck Assoc. (1989) could not find any correlation between the ramping and the incidence of pothole trapping, nor was there any correlation between the ramping rate and steelhead fry stranding during the summer. In both cases, stranding occurred regardless of the ramping rate.

ix. **Time of year.** Small fry are highly vulnerable to stranding and are present in the streams only at certain times of the year. Chinook, coho, pink, and chum fry emerge during late winter and early spring while steelhead emerge in late spring through early fall (Olson 1989). Fingerlings, smolts, and adults are vulnerable to stranding in other seasons; however, less restrictive ramping criteria is often sufficient to protect them.

x. **Time of Day.** For at least some species, the incidence of stranding is influenced by the time of day. Chinook fry are less dependent on substrate for cover at night and thus are less vulnerable to stranding at night (Woodin 1984). Two studies (Stober et al. 1982, Olson 1990) concluded that steelhead fry are less vulnerable during the day, presumably because this species feeds during the day. However, two other studies (Beck Assoc. 1989, Monk 1989) found no difference in the rate of steelhead fry stranding relative to day and night.

xi. **Duration of Stranding.** Salmonids respire using their gills and do not survive out of water for more than ten minutes. Thus beaching is always fatal. Juvenile salmonids trapped in side channels and potholes can survive for hours, days, or under favorable circumstances, months (author's pers. obs.). However, many trapped fish die from predation, temperature shock, and/or oxygen depletion. Survivors that are rescued by higher flows are probably in poorer condition than fish in the free-flowing channel.

xii. **Flow Stability Prior to Drop in Flow.** Some observations suggest that a highly stable flow regime for a week or more prior to a flow fluctuation will increase the incidence of fry stranding (Phinney 1974b). Two hypotheses might explain this observation. One hypothesis states that after long periods of stable flow, more fry are available for stranding. In other words, a major flow reduction after a week of stable flows strands seven daily cohorts of emerging fry at once, rather than one cohort when fluctuations occur daily. An alternative hypothesis is that juveniles become accustomed to residing and feeding along the margins of a stream either as a behavioral response to stable flows or in response to aquatic invertebrate populations that thrive along the water's edge under stable flows. These hypotheses should be thoroughly tested before they are applied to mitigation practices.

c. Juvenile Emigration (Salmonid Drift)

Flow fluctuations in an experimental stream channel caused juvenile chinook to emigrate downstream (McPhee and Brusven 1976). The pre-test rate of emigration under stable flows was about one percent a day. Severe flow fluctuations (from 51 liters/sec to 17 to 3 to 51 with each flow held for 24 hours) caused 60 percent of the chinook to emigrate. A high rate of emigration continued even after initial flows were reestablished. A less-severe daily fluctuation in flow (between 51 and 17 liters/sec for four 24-hour periods) caused 14 percent of the chinook to emigrate. Alternating flows between 51 liters/sec and 17 liters/sec every 24 hours cause a greater rate of emigration than alternating the same flows every 12 hours. Most of the emigration occurred at night, a behavior observed in aquatic invertebrates.

The behavioral response to flow fluctuations and how this may affect the juvenile salmonid rearing capacity is not well understood. Under conservative ramping requirements, flow fluctuations may cause downstream emigration, driving many fish habitat that may be less desirable or overcrowded and leaving upstream rearing habitat under-utilized. This could be a particular concern in a stream with a falls or other barrier that prevents juveniles from returning upstream.

d. Increased Predation

Phillips (1969) suggested that juvenile fish forced from the river margins as a result of declining flows suffer from predation by larger fish. This effect has not been documented anywhere to my knowledge; however, it is a credible hypothesis under some circumstances.

e. Aquatic Invertebrates

Like fish, aquatic invertebrates are not necessarily adapted to unnatural drops in flow. Cushman (1985) extensively reviewed the effects of flow fluctuations on aquatic life, especially aquatic invertebrates. Interested readers should read this review. Rather than his duplicate efforts, I will briefly summarize the topic and discuss several regional studies.

Research on the effects of flow fluctuations on aquatic invertebrates in the Pacific Northwest is limited, although more information is available elsewhere in North America. These studies suggest that aquatic invertebrates can be severely impacted by flow fluctuations. Fluctuations substantially reduce invertebrate diversity, total biomass and changes the species composition under most circumstances. One study from the Skagit River found that flow fluctuations had a greater adverse impact on the aquatic invertebrate community than a substantial reduction in average flow (Gislason 1985). The reduction in the aquatic invertebrate production can impact salmonid production as a result of reduced feeding (Cushman 1985; Schlosser 1982).

Additional research is needed on the effects of flow fluctuations on aquatic invertebrates in the Pacific Northwest. However, a thorough study would be a formidable task. It would involve many species with different life cycles, behavioral responses, lethal responses, and contributions as prey to salmonids. Populations of some species may change rapidly under normal conditions, thus it may be difficult to associate cause and effect.

Flow fluctuations can impact the aquatic invertebrates in the following ways:

i. **Stranding.** Flow fluctuations can strand many species of aquatic invertebrates, much in the same way fish can become stranded (Phillips 1969; Gislason 1985). Death may result from suffocation, desiccation, temperature shock, or predation.

ii. **Increased Drift.** Many aquatic invertebrates are sensitive to reductions in flow, and respond by leaving the substrate and floating downstream. This floating behavior is called **drift.** Night time drift is normal; however, drift becomes highly elevated under unnatural fluctuations in flow (McPhee and Brusven 1975; Cushman 1985). This elevated drift may be an emergency response to avoid stranding, or a response to overcrowding of the inter-gravel habitat, or it may be a response by aquatic species are adapted to a narrow range of water velocity. This response may temporarily increase fish food supply (McPhee and Brusven 1975), but when repeated fluctuations occur, many species are flushed out of river reach and the aquatic invertebrate biomass usually declines, often substantially (Cushman 1985, Gislason 1985). Elevated drift also occurs in response to sudden increases in flow, which captures terrestrial insects from the river banks and scours some aquatic invertebrates from the river substrate (Mundie and Mounce 1976).

iii. **Detritus Feeders.** Under stable flow conditions, floating detritus (leaves, woody debris) accumulates on the shores of the river as a result of current and wind action on sand or gravel substrate. This detritus remains close to the river margin and often remains damp for days or weeks at a time. Under fluctuating flows, this organic detritus becomes suspended (Mundie and Mounce 1976) and is flushed out of the river or redeposited at the high waterline where it desiccates during low flow periods. As a result the invertebrate detritus community is less capable of exploiting this resource.

iv. **Herbivorous Invertebrates.** Impacts are similar to that on the detritus community. Algae grows on exposed rock surfaces on which herbivorous aquatic invertebrates graze. Fluctuations desiccate and disrupt the growth of the exposed algae (Gislason 1985) and reduces access by herbivores.

f. Redd Dewatering

Research has extensively documented the lethal impact of redd dewatering on salmonid eggs and alevins (i.e., larval fish) (Fraley and Graham 1982, Fraser 1972, Satterthwaite et al., 1985, Fustich et al., 1988). Salmonid eggs can survive for weeks in dewatered gravel (Stober et al., 1982; Reiser and White 1983; Becker and Neitzel 1985; Neitzel et al., 1985), if they remain moist and are not subjected to freezing or high temperatures. The necessary moisture may originate from subsurface river water or from ground water. If the subsurface water level drops too far, the inter-gravel spaces will dry out, and the eggs will desiccate and die. Thus redd dewatering is not always lethal or even harmful to eggs. However, site specific conditions, weather and duration of exposure all affect survival.

Because alevins rely on gills to respire, dewatering is lethal (Stober et al., 1982, Neitzel et al., 1985). Alevins can survive in subsurface, inter-gravel flow from a river or ground water source. If inter-gravel spaces are not obstructed with pea gravel, sand, or fines, some alevins will survive by descending through inter-gravel spaces with the declining water surface (Stober et al., 1982). Both alevins and eggs may die from being submerged in stagnant water. Standing inter-gravel water may lose its oxygen to biotic decay, and metabolic wastes may build up to lethal levels.

A redd can be dewater between spawning and hatching without harm to the eggs under some circumstances, and in one situation, a hydropower facility is operated to allow limited redd dewatering (Neitzel et. al. 1985). However, in most Pacific Northwest rivers, anadromous fish spawn over an extended period. Different species spawn in different seasons and individual species may spawn over a range of two to six months. As a result, when eggs are present, alevins and fry are also present, both of which are highly vulnerable to flow fluctuations.

g. Spawning Interference

Bauersfeld (1978b) found that repeated dewatering caused chinook salmon to abandon attempts to spawn and move elsewhere, often to less desirable or crowded locations. Hamilton and Buell (1976) performed a highly detailed study using observation towers situated over spawning beds to track activity on the spawning bed and to observe individual tagged fish. They observed that spawning chinook were frequently interrupted by flow fluctuations. Females repeatedly initiated redd digging, and then abandoned the redd sites when flows changed. They concluded that flow fluctuations decreased viability due to untimely release of eggs, failure to cover eggs once they were released, and a failure of males to properly fertilize eggs laid in incomplete redds. Other researchers had conflicting conclusions. Stober et. al. (1982) noted that chinook salmon successfully spawned in an area that was dewatered several hours a day, and Chapman et. al. (1986) found that eight hours a day of dewatering still permitted successful spawning.

5. The Hydraulic Response to Flow Fluctuations. This section describes the downstream physical response to fluctuation events.

a. Attenuation

The ramping rate attenuates as a function of the distance downstream from the source of a fluctuation event (e.g., Nestler, Milhous, and Layzer 1989). The characteristics of the river greatly influences this attenuation. A fluctuation in flow passing through a narrow bedrock river channel will experience little or no attenuation. Pools, side-channels, and gravel bars attenuate the ramping rate by storing water from higher flows and release this water gradually. Tributary inflow will attenuate the ramping rate and the ramping range. Hydraulic equations (e.g., unsteady flows; Chow 1959 p. 528) exist to describe these responses. A verbal description and examples of downstream responses are provided below.

Figure 2 shows the progression of a fluctuation as it moves downstream past four U.S. Geological Survey gages on the Skagit River. The "hump" that progresses from left to right represents an experimental flow fluctuation requested by fisheries agencies to determine ramping rates and stranding activity. Table 5 tabulates the ramping range, maximum ramping rate, and total duration of decline in flow at each station in response to this event. The ramping range and ramping rate become less as the fluctuation event progresses down the river.

In a similar study in the Deschutes River (Oregon), the ramping range attenuated from 1.6 feet to 1.2 feet over 55.7 miles of river. The ramping range was 0.35 feet 99.7 miles downstream of the powerhouse (Phillips 1969). Attenuation does not occur in uniform increments over distance. Figure 3 plots the data from a load rejection test at the Snoqualmie Falls Project conducted on July 17, 1990. Observers monitored staff gages at six sites downstream from the powerhouse. The farthest site was 4.6 miles downstream. Note that the contour of the water surface overtime was different at each site. Furthermore, the maximum decrease in stage did not occur at the site closest to the powerhouse but at the fifth of six sites. The river channel shape and gradient in the vicinity of each site influences the stage contour. Thus the interpolation and extrapolation of data to derive estimates of ramping rates and ramping ranges for other sections of the river should be avoided. Never-the-less, significant attenuation is evident when the sixth experimental gage data is compared with data from a U.S. Geological Survey gage located 14 miles downstream (Figure 4).

b. Lag Time

Lag Time can be the time it takes for a fluctuation to pass from one place to another on a river. In Figure 2, it took over 7 hours for a fluctuation event to pass through 40 miles of a large river at medium flow. In Figure 4, it took over 5 hours for a fluctuation event to pass through 17.2 miles of medium-sized river at low flows. Phillips (1969) documents a 20.5 hour time lag on

The following bold scripted terms are defined:

Dam facilities have substantial water storage and a powerhouse at the base of the dam. **Run-of-the-river facilities** typically have a small **diversion dam** which diverts water into a **penstock**, a pipe that delivers water to the powerhouse, which is located farther down the river.

A hybrid of these two types of facilities is **dam and penstock facility** which has a powerhouse located some distance downstream of a large dam. Some types of operational impacts and mitigation activities apply only to certain types of facilities, thus it is important in understand these distinctions.

Other classification schemes many be helpful in identifying fluctuation concerns or mitigation actions. Does the facility have **seasonal storage, daily storage**, or **no storage**? How many turbines does it have? Many projects do not fit neatly into any classification scheme because of multiple purposes (irrigation or municipal diversions, recreation, flood control) or because of peculiarities in design or configuration. Thus, there is no single method for assessing fluctuation risks nor is the a single set of mitigation criteria that can be applied.

The **upstream reach** is the segment of the river above the diversion forebay or reservoir. The **bypass reach** is the segment of the river or stream between the diversion structure or dam and the powerhouse. Dam facilities do not have bypass reaches. The **downstream reach** is the segment of the river or stream below the powerhouse discharge.

The public often perceives run-of-the-river facilities as low impact alternatives to dam facilities because water is simply withdrawn from the bypass reach without

a. Peaking

Utilities often operate hydropower facilities to follow daily changes in power demand, a practice called **load following**. Power demand is higher during the day, especially in the morning and, to a lesser extent, in the evening. For many utilities, the capacity for load following is a premium power resource, and hydropower is the preferred means of load following. Thermal power plants, including coal, gas, oil, and nuclear facilities, wear down faster from the constant heating and cooling that results from load following, and usually operate less efficiently. Thus, hydropower facilities with seasonal or daily storage are often operated for load following (Carter and Trouille 1989).

When load following occurs, the powerhouse discharge fluctuates daily, an effect defined as **peaking**. Peaking is the most widely documented source of fish stranding. Biologists and fishermen have observed major fish kills from peaking (Thompson 1970; Graybill et al., 1979; Phinney 1974; Bauersfeld 1977, 1978; Becker et al., 1981). These fluctuations often occur daily for weeks or months resulting in severe cumulative impacts to fish populations. Whenever possible, a powerhouse located at the head of a free-flowing river should not be operated for peaking, especially during fry emergence and early stream residence. In a river with multiple dams, utilities can operate the upper dams for peaking, while discharge from the lowest dam remains constant (i.e., a **re-regulating reservoir**). Multiple dam systems suitable for load following and stable discharge are abundant in the Pacific Northwest. Utilities should use these opportunities to follow load demand.

When peaking is necessary, these discharges should be ramped down (Phinney 1974), and timed seasonally and/or daily, (Woodin 1984, Olson 1990). For all projects, biologists should identify a critical flow to minimize stranding.

b. Low Flow Shutdowns

Most projects have a minimum turbine flow below which it is impossible or impractical to operate the turbine(s) for power generation. In addition, a minimum flow is usually required to maintain the aquatic habitat in the bypass reach. For run-of-the- river facilities, power generation cannot occur unless river flow at the intake is greater than or equal to the combined bypass flow requirement and minimum turbine flow. These projects will have low flow shutdowns between 1 to 20 times a year depending on run-off patterns and bypass flow requirements. Dam facilities with seasonal storage can operate for years without a low flow shutdown.

c. Low Flow Start-ups

Run-of-the-river projects will cause a drop in flow in the bypass and downstream reaches during powerhouse start-ups (See Figure 5). In these situations, operators must ramp flows at the start of power generation to reduce stranding. Usually the ramping rates will be dictated by what is necessary to protect fish in the bypass reach. By the time the fluctuation reaches the downstream reach, attenuation from the powerhouse discharge, tributary inflow, and sometimes in-channel storage will usually moderate the ramping rate.

d. Powerhouse Failures

Powerhouse failures are disruptions of the penstock flow originating from the powerhouse. These disruptions result from powerhouse mechanical problems or **load rejection**, which is the inability of the utility line to receive power generated from the turbines. Load rejection requires immediate action to avoid damage to the turbine bearings and penstock, since the turbine will spin out of control without the resistance of the magnetic fields in the generator. Operators traditionally responded to powerhouse failures by cutting off penstock flow, which suddenly drops flow in the downstream reach. Biologists should expect powerhouse failures at any facility. My experience is that they occur most frequently at small, run-of-the-river facilities with a single turbine, remote control operation, and a long rural utility line.

Flow continuation is the mechanical capacity to maintain flow through the penstock during powerhouse failures. Flow continuation is now a standard design criteria for new run-of-the-river facilities in Washington State. Flow continuation can be provided by a flow bypass valve which allows flow to pass around the turbine when in operation. Pelton turbines can be designed with deflectors to safely pass flow through the turbine without generating power. Pelton deflectors might serve as a substitute for a flow bypass valve, although further evaluation is needed. With flow continuation equipment, power generation can be shut off and on without ramping flow up or down, a feature that will appeal to some utilities. Flow continuation can also reduce human safety risks associated with rapid increases in flow.

The flow continuation equipment, especially bypass valves, are expensive, and developers may try to install equipment that cannot provide sustained flow continuation. Fishery agencies should specify the duration of flow continuation as part of the design criteria. It may be appropriate to waiver flow continuation requirements when river flow is >10 percent of the annual flow exceedence. During very high flows, suspended fines can wear or damage equipment, and flow continuation probably offers little benefit to aquatic life.

If maintenance or repair activity absolutely requires the penstock flow to be shut off, the operator can ramp the discharge immediately. Since flow disruption is inevitable, there is no benefit from flow continuation. Likewise, if the operator knows that power generation will be shut down for several days, ramping can start immediately. There is no purpose in subjecting the flow continuation equipment to unnecessary wear, and in some cases, fish and aquatic life in the bypass reach will benefit from sustained higher flows.

e. Intake Failures

Intake failures cover all penstock flow disruptions that occur at the intake structure. This may result from the accumulation of debris, the failure of fish screen cleaning equipment, or failure of the dam and associated gates to divert water into the intake. My experience to date suggests that intake failures are less frequent than powerhouse failures. Many intake failures result from a gradual accumulation of debris on the screens and trash racks and tend to ramp down slowly until the minimum operating flow is reached. When an intake failure occurs, flow continuation is impossible except at dam facilities with multiple intake and discharge locations. Furthermore, the capacity to ramp flows after intake failures may be limited. Therefore, prevention is the preferred means of reducing intake failures. The diversion structure should be designed and maintained to minimize intake failures. Design criteria for mechanical screen cleaning and trash control equipment should be considered.

When an intake failure occurs, operators should attempt to ramp with the residual water in the penstock, although meeting ramping rate criteria established for powerhouse failures is often impossible.

Intake failures are most likely to occur during the first one or two high flow events of the fall. These initial high flows pick-up leaf litter and other debris that have accumulated in the stream channel over the summer and early fall. This debris frequently overloads the debris control equipment (pers. comm. with several small hydro operators). More frequent maintenance is normally required at this time. One run-of-the-river facility in Washington State addresses this problem by foregoing power generation until after the first one or two major storms.

f. Cycling

For a run-of-the-river facility, the minimum river flow needed for power generation is the sum of the minimum bypass flow requirement and the minimum turbine flow. When the river flow is less than this sum but greater than the minimum bypass flow requirement, it is possible to continue operation intermittently by using the reservoir, surge tank, and/or penstock for storage. The operator stores water in excess of the minimum bypass flow. When the storage is full, power can be generated for a short time. This practice fluctuates flow in the downstream reach many times a day.

Cycling is simply a way to generate power when flow is not enough for continuous or efficient operation, and it is not an attempt to follow load demand. Cycling may also occur as a result of an improperly programmed automated powerhouse which shuts off and on near minimum operation flows. An example of cycling is shown in Figure 6.

The biological impacts of flow fluctuations have not been formally evaluated. However, cycling is likely the most damaging type of hydropower flow fluctuation, especially when compared to the negligible amount of power generated. Cycling will normally occur at low stream flows when the salmonids would be most vulnerable to fluctuations. Fish habitat will be most limited at low flow, and the effect on fish populations is probably severe. Massive stranding of emerging fry is likely during parts of the year. Cycling would probably reduce primary and secondary productivity substantially. Until research can conclusively demonstrate that cycling is not harmful, cycling should be forbidden. If a developer is concerned with utilizing sub-operational flows, a smaller auxiliary turbine can be installed.

g. Multiple Turbine Operation

If a powerhouse has two or more turbines, operators can cause abrupt changes in flow when changing the number of turbines in operation. Biologists should specify for a smooth transition of flow when the number of turbines are reduced. Most modern turbines are designed to operate over a broad range of flows; thus, a smooth transition is relatively easy to accomplish. **Modified peaking** and **modified cycling** occur when power generation is switched off and on for some turbines but one or more turbines are running continuously. These operations will not have the impact of a single turbine shutting off and on. However, biological impacts should be expected in most cases. Modified cycling should be discouraged.

h. Forebay Surges

The hydrographs from a new run-of-the-river project indicated a surge of water every time the powerhouse started generation (Figure 6). This was probably caused by a drop in head at the intake during start-up. These **forebay surges** were relatively insignificant during medium or high flows but appeared to cause severe fluctuations at low flows. The prevalence of this problem among hydropower facilities is unknown. However, facilities should be designed and operated to avoid forebay surges.

i. Reservoir Stranding

Hydropower activity can cause stranding in forebays and reservoirs. The author has observed stranding of a rainbow trout in a very small forebay at a run-of-the-river facility. The forebay water level was fluctuating as a result of cycling.

Reservoir or forebay maintenance drawdowns sometimes cause stranding. In large reservoirs, stranding is routinely anticipated as one of the consequences of drawdowns, and it is sometimes employed as a method of eradicating undesirable fish. However, stranding also occurs in the forebays of run-of-the-river projects. In one case, the author observed a run-of-the-river project with a narrow forebay of about one quarter acre which was drawn down for annual maintenance. Despite an active stream flowing through the forebay and through a gate in the dam, about 30 juvenile and adult trout were trapped in a shallow, concrete depression in front of the intake trash rack. The operator agreed to electroshock and move these fish back to the stream as part of every maintenance shutdown. Intake structures should be designed to drain completely without leaving pools of water.

j. Tailwater Maintenance and Repair Activities

All hydropower facilities will eventually require inspections, maintenance, and repair. For most facilities, these activities occur during low flow periods or during operational shutdowns without disrupting flow. However, if a dam facility has only one discharge site or tailrace, it is often impossible to inspect or repair the structure or equipment submerged in the tailwater without completely or substantially disrupting the flow of the river. Phillips (1969) describes a severe fluctuation resulting from a tailwater inspection. Ideally, dam facilities should have multiple points of discharge to avoid these infrequent but severe impacts.

k. Frequency of Fluctuations at Run-of-the-River Facilities

Run-of-the-river facilities can cause flow fluctuations as a result of low flow shutdowns, start-ups, powerhouse failures, intake failures, cycling, and forebay surging. From the limited data available to the author, the frequency and type of flow fluctuations are quite variable. Many new or proposed run-of-the-river facilities are located in remote mountainous areas, serviced by rural utility lines, and operated by remote control. At one new single turbine run-of-the-river facility (Weeks Falls project on the SF Snoqualmie River), approximately 150 powerhouse shutdowns were recorded during the first 23 months of operation, including 46 during sensitive low-flow periods (Figures 6 and 7). After four years of operation, it was still experiencing a high frequency shutdowns. However older, utility-owned, run-of-the-river facilities often have a relatively low frequency of shutdowns. Facilities, such as the Yelm Project on the Nisqually River and Snoqualmie Falls Project on the Snoqualmie River, are managed for steady base load power production. The operators of these facilities have a vested interest in maintaining stable power production and have had many years to mechanically resolve the causes of shutdowns. Frequency of shutdowns is probably less than five per year, although the author has not been able to acquire actual data from these utilities.

7. Mitigation Requirements and Considerations

Mitigation negotiations require a timely development of information and, in response to this information, terms and conditions for construction, further evaluation, and operation. This section provides an example on how and when to address the issues and develop criteria.

Washington Department of Fisheries (WDF) requires full mitigation for all fish kills and all losses of anadromous fish habitat (i.e., no net loss). Owners of existing facilities up for relicensing must make all reasonable attempts to avoid harm to anadromous fish and correct facility activities or features that are currently causing habitat losses. If salmon production cannot be restored to preproject levels, alternative mitigation, either in the form of off-site enhancement, or hatchery production, will be requested. Proposed new facilities must demonstrate that no impact on the salmon resource will occur before WDF supports construction. If there is any doubt as to whether certain operation procedures and/or facility designs are harmful to fish, the burden of proof is on the developer or utility to study the potential impact and demonstrate that no harm will occur.

These relatively high standards of mitigation are a policy response to the high value the public places on the anadromous fish resource, and the historical and ongoing losses of fish and fish habitat as a result of hydropower development. In addition, the Indian treaty fishing rights implicitly includes preservation of the freshwater habitat needed by wild salmonids. Current policy precludes new hydropower development in a river reach accessible to anadromous fish. Resource agencies in other areas may need to interpret the criteria presented below in light of their own policies. Furthermore, criteria should be modified to protect local species which may have different life cycles, behaviors, and periods of vulnerability.

Mitigation activities for flow fluctuations continue throughout the development of a project, including consultation, licensing and operations. The following discussion parallels the U.S. Federal Energy Regulatory Commission's licensing procedures. In general, mitigation criteria for rivers are well established. However, more research is needed to fully understand the impact of flow fluctuations on streams (i.e., average annual flows less than 500 cfs), and at this time, WDF does not have a clearly defined set of criteria to apply to smaller projects. Criteria for these smaller projects will be influenced by site specific observations and future research.

a. Consultation

During consultation, the agencies identify concerns and informational needs, and the applicant collects information and performs studies as requested.

The applicant should identify the fish species present and locate the barriers to anadromous fish passage. This information will give biologists a rough idea of which impacts may occur. Pre-project information on flow, species composition, and fish also serve as a baseline to compare against post-construction information. A life history schedule of the important fish species should be developed to determine time periods when stranding or redd dewatering are likely to occur.

i. Under most circumstances, permanent ramping rate criteria can be established for projects located on rivers, as listed below. These criteria also serve as interim ramping rate criteria for facilities located on streams:

Season	Daylight Rates[3]	Night Rates
February 16 to June 15[1]	No Ramping	2 inches/hour
June 16 to	1 inch/hour	1 inch/hour

iii. If the applicant wants to peak flow discharges to follow load demand, he should demonstrate that the load following capacity is needed and not available elsewhere. The applicant should indicate the times of the year this peaking is anticipated and consult with the agencies on the biological impacts and potential mitigative actions. However, in productive river systems, peaking may simply be an unacceptable mode of operation. Currently, WDF opposes peaking operations at proposed facilities with free-flowing downstream reaches accessible to salmon.

b. Licensing

During licensing, biologists should specify terms and conditions that minimize the occurrence of fluctuations. When fluctuations are unavoidable, they should specify terms and conditions that establish ramping rates and ramping schedules that permit a smooth transition in flow. Some or all of the following terms and conditions can be applied to achieve these objectives.

i. All proposed run-of-the-river facilities should have the mechanical capacity to maintain flow continuation for 48 hours. When a powerhouse failure occurs, flow continuation should be maintained a minimum of 24 hours. During salmon fry emergence, flow continuation should continue beyond 24 to avoid ramping during daylight hours. This additional time should also take into account the lag time it takes for the fluctuation to reach sensitive downstream rearing habitats. Under most circumstances, more lenient flow continuation criteria can be specified at high flows (i.e., above the 10 percent annual flow exceedence).

   Dam facilities should have the capacity for indefinite flow continuation. A value should be installed in the dam to permit flow discharges independent of the turbines.

ii. Proposed facilities shall have the designed capacity to down ramp the powerhouse discharge at 1 inch of stage per hour at the transect approved by agency biologists during consultation. For run-of-the-river projects, the diversion and intake structure should have the capacity to ramp bypass flows at 1 inch per hour. If necessary, existing facilities should upgrade their equipment to meet the 1 inch per hour ramp capacity.

iii. Agency biologists will assist the applicant in determining the critical flow, in other words, the flow above which the risks of stranding are negligible. This may best be determined by observing the key stranding areas at different flows.

iv. For existing dam and penstock facilities without flow continuation equipment, operators can offset fluctuations in the downstream reach by increasing the bypass flow prior to a powerhouse shutdown. Once the higher bypass flow reaches the powerhouse, the powerhouse can ramp down at a relatively fast rate. Obviously, fluctuations from unanticipated powerhouse shutdowns cannot be prevented with this method.

v. In the event of an intake failure at a run-of-the- river facility, the powerhouse should be operated to ramp flows down as smoothly as possible using residual water in the penstock and surge tank. Intake fish screens shall be cleaned and maintained as often as necessary to prevent intake failures. Under most circumstances, mechanical cleaning equipment should be required.

vi. Cycling is forbidden.

vii. Applicants should design and operate projects to avoid forebay surges.

viii. If peaking is permitted, the resource agencies shall determine seasonal and daily limitations on this mode of operation.

c. **Operations**

i. The operation manual shall explicitly list the operation procedures needed for flow continuation, ramping and maintaining the intake screens. Critical flows must be identified.

ii. Utilities should operate large storage facilities to avoid redd desiccation in spawning areas below dams. Flow discharges during spawning should be kept relatively stable, but not so low that the migration and spawning activity are impeded and not so high that water storage is reduced and there is risk of redd dewatering during incubation.

Biologists and utilities often have difficulty identifying a fixed operating procedure, especially when the utility has to manage flow releases for other objectives, such as summer reservoir recreation (i.e., keep reservoir pool high and stable), winter flood control (i.e., draw reservoir pool down), and power demand. Since most stocks of salmon spawn just before or during the heavy rain season (late fall to early winter), the desirable strategy is to increase flows during the spawning season only when necessary to meet flood control requirements <u>and avoid reducing flows</u>. When spawning is complete, excess water is released if necessary, and a minimum incubation flow is established. This strategy maintains greater flow flexibility during incubation and emergence. Under some circumstances, a written operation plan that takes into account all possible hydrologic scenarios can be developed. However, sometimes in-season communications between biologists and operators provide the best means of protecting redds.

iii. For projects located on streams, the permanent ramping rates may be established after construction on the basis of site-specific observations and any new research on the impact in streams.

8. Field Methods. This section contains notes and references concerning field methods.

a. A Word of Caution.

Investigators should carefully consider whether flow fluctuation events staged to evaluate ramping or stranding are necessary, especially when fish kills are anticipated. A number of the author's professional predecessors have observed that the souls of these dead fish come back to haunt you in the form of irate fishermen and agency administrators, especially when the news media reports the event. In one test, researchers abruptly canceled an experiment and restored initial flows when 'tens of thousands' of stranded juvenile salmon were observed during the initial drop in flow (Hamilton and Buell 1976). Whenever possible, researchers should try to assess impacts that occur from routine hydropower operations, rather than staging events of larger magnitude. If you are only testing the hydraulic response, select a time of the year when salmonid fry are least vulnerable.

b. Estimation of Stranding Losses

Direct counts of stranded fish as a result of flow fluctuations may be useful as indices. However, researchers have had difficulty making reliable and unbiased estimates of total mortality. A complete survey of a river system during a fluctuation event requires a very large group of observers. Many stranded juvenile fish, especially fry, are hidden in the substrate where they seek refuge during declining flows. Out-of-sight salmonid stranding occurs in gravel (Phinney 1974, Bauersfeld 1978), mud (Becker et al., 1981), and vegetation (Phillips 1969, Satterthwaite 1987). Under laboratory conditions which permitted total enumeration of test fish, Monk (1989) counted surface and subsurface stranding on three types of gravel substrate. The ratios of surface to subsurface stranding on fine gravel, medium gravel and cobbles was 1:0.01, 1:1.5 and 1:1.0 respectively for chinook fry (mean fork length 46.5 mm), and 1:0.06, 1:5.6 and 1:2.9 respectively for steelhead fry (mean fork length 33 mm).

Scavengers and predators often remove fish before observers can count them. Crows often start foraging as soon as flows decline (Phinney 1974, Fiscus 1977, Satterthwaite 1987, author's pers. obs.). Other animals, ranging from slugs to humans, have been observed taking stranded fish. Both Phinney (1979) and Bauersfeld (1978) tried to establish habitat index areas for stranding observations. Counts were expanded to estimate losses in similar

stranding within limited index areas. In addition, they had trouble estimating the total area exposed from aerial photographs because of shadows casted by trees and high banks. As a result, tenuous assumptions were necessary in deriving estimates of total mortality. Other studies simply abandoned attempts to estimate losses (Phillips 1969, Phinney et al., 1973, Becker et al., 1981) or did not attempt to estimate losses. Future estimation of stranding losses should be approached with cautious methodology and realistic expectations.

c. **Ramping Rate Tests**

Under some circumstances, it is necessary to evaluate the hydraulic response to a change in flow over an extended area downstream of the fluctuation source. If possible, testing should occur in the fall prior to spawning. At this time salmon have grown substantially, although steelhead fry are still rather vulnerable. Prior to testing, the utility and resource agencies should meet and agree on the number of tests to be performed, number and location of observation sites, and date and time to perform them. Multiple tests may be necessary to evaluate several different flows or to repeat earlier tests that were unsatisfactory.

impacts of flow fluctuations in the bypass and downstream reaches. A hydropower trade journal report on methods of balancing load following with fish and recreational needs (Carter and Trouille 1989), relied exclusively on the IFIM methodology and failed to consider lethal and behavioral impacts of flow fluctuations. A comprehensive review of environmental mitigation at hydropower projects (Sale et al., 1991) addressed in considerably detail the variety of instream flow requirements negotiated at hydropower projects; however, the issue of flow fluctuations was limited to one brief sentence. Site-specific studies that give a balanced treatment of the effects of both flow alterations and flow fluctuations, such as Hamilton and Buell (1976), are relatively rare.

The IFIM methodology is a valuable and widely accepted procedure for measuring change in fish habitat and has legitimate application to situations involving flow alterations. However, it is a complex and engrossing methodology that often distracts from other biological effects of hydropower development.

Are the impacts of flow fluctuations more significant than flow alterations? I don't believe there is an answer to this question. The magnitude of each impact is a site-specific function of species, channel size, channel morphology, and facility operations. Furthermore, these impacts are measured in different units (i.e., stranding mortality versus usable habitat area). However, it should be emphasized that lethal effects of flow fluctuations on salmonids are widely documented in the Pacific Northwest. By contrast, experimental verification of the relationship between habitat units and salmonid productivity is sparse.

Recent enhancements of the IFIM methodology are showing increasing ability to address the effects of flow fluctuations. Prewitt and Whitmus (1986) propose some methods for assessing relative stranding risks resulting from different changes in flow. These methods might be useful when the relative risks of different operational procedures must be compared. Nestler et al. (1989) describe a method for assessing the habitat effect of peaking on fish that are capable of moving to suitable habitat. Thuemler et al. (1991) added a method of measuring the loss of habitat for immobile aquatic animals as a result of peaking discharges.

However, the IFIM methods have not been developed to the point where it can be a primary tool for assessing flow fluctuations. The biological response, including lethal effects, delayed effects, and behavioral effects are not sufficently understood to permit reliable modelling. When there is a "no net loss" objective, a complex study is unnecessary. Ramping rates, ramping schedules, and critical flows can often be determined by biologists from the hydraulic, hydrological and biological characteristics of the tributary and from comparable studies.

b. Needs for Additional Research

In Washington State, the current flow fluctuation mitigation criteria are based on research in medium and large rivers. Most new hydropower facilities built in the next decade will be small run-of-the-river facilities located on streams (<500 cfs average annual flow). Research is needed to develop criteria for small rivers and streams to protect the species that prefer these habitat (coho, steelhead, and resident trout). The behavioral effects of fluctuations on juvenile salmonids requires further study, especially as they apply to small streams.

A study by Gilsason (1985) and other studies reviewed by Cushman (1985) suggest that the impact of peaking in Washington State rivers is under-estimated because of impacts to the aquatic invertebrate community. Research is needed to better measure this impact, and also identify the relationship between invertebrate production and salmonid production.

Current methods for estimating stranding losses are inadequate to accurately assess loss of production. Development of alternative methods would be helpful.

Anadromous adults much more numerous and more fecund, and thus produce a much greater density of juveniles. Obviously, observers are far more likely to report the stranding of large numbers of juveniles than small numbers.

It is possible that limited fry stranding will have little effect on resident populations because production is limited by the adult rearing habitat and, thus, juvenile to adult survival is not a major limiting factor.

10. References Cited

Bauersfeld, K. 1977. Effects of Peaking (Stranding) of Columbia River Dams on Juvenile Anadromous Fish below the Dalles Dam, 1974 and 1975. WDF, Olympia, WA Tech. Rep. 31:117 pp.

Bauersfeld, K. 1978. Stranding of Juvenile Salmon by Flow Reductions at Mayfield Dam on the Cowlitz River. WDF, Olympia, WA, Tech. Rep. 36:36 pp.

Bauersfeld, K. 1978b. The Effect of Daily Flow Fluctuations on Spawning Fall Chinook in the Columbia River. WDF, Olympia, WA, Tech. Rep. 38:32 pp.

Beck Associates, R. W. 1989. Skagit River Salmon and Steelhead Fry Stranding Studies. Prepared by R. W. Beck Associates for the Seattle City Light Environmental Affairs Division, March 1989. Seattle, WA, 300 pp.

Becker, C. D., D. H. Fickeison and J. C. Montgomery. 1981. Assessments of Impacts from Water Level Fluctuations on Fish in the Hanford Reach, Columbia River. Pacific Northwest Laboratory, Batelle Memorial Institute, Richland, Washington.

Becker, C. D., and D. A. Neitzel. 1985. Assessment of Intergravel Conditions Influencing Egg and Alevin Survival During Salmonid Redd Dewatering. Env. Biol. of Fishes. 12:33-46.

Bovee, K. D. 1982. A guide to stream habitat analysis using the instream flow incremental methodology. FWS/OBS 82/86. US Fish and Wildlife Service, Washington D.C.

Carter, E. F. and B. J. Trouille, 1989. Balancing Power and Other Instream Uses. Hydro Review. August 1989:96-108.

Chapman, D. W., D. E. Weitkamp, T. L. Welsh, M. B. Dell, and T.H. Schadt. 1986. Effects of River Flow on the Distribution of Chinook Salmon Redds. Trans. Amer. Fish. Soc. 115:537-547.

Chow, Van Te. 1959. Open Channel Hydraulics. MacGraw Hill Book Company. New York. 680 pp.

Cushman, R. M. 1985. Review of Ecological Effects of Rapidly Varying Flows Downstream from Hydroelectric Facilities. N. Amer. J. of Fish. Management 5:330-339.

Frailey, J. J. and P. J. Graham. The Impact of Hungry Horse Dam on the fishery in the Flathead River. Final Report. US Bureau of Reclamation, Boise, Idaho.

Fiscus, G. 1977. This citation includes four short reports: (1) Cedar River Fish Damage Observations and Reports on February 18, 1977; (2) Report of Cedar River Fish Kill On March 1, 1977; (3) Report of Cedar River Fish Kill on March 8, 1977 (No. 3); and (4) Investigation of Cedar River Flow Fluctuation on May 21, 1977. WDF. Internal memos. Olympia, WA.

Fraser, J. C. 1972. Regulated discharge and the stream environment. in R. T. Oglesby, C. A. Carlson and J. A. McCann, editors. River Ecology and Man. Academic Press. New York, New York.

Futish, C. A., S. E. Jacobs, B. P. McPherson, and P. A. Frazier. 1988. Effects of the Applegate Dam on the biology of Anadromous Salmonids in the Applegate River. Prepared by Research and Development Section, Oregon Dept of Fish and Wildlife for US Army Corps of Engineers. DACW57-77-C-0033. 105 pp.

Gislason, J. C. 1985. Aquatic Insect Abundance in a Regulated Stream under Fluctuating and Stable Diel Flow Patterns. North Amer. J. of Fish. Manag. 5:39-46.

Graybill, J. P., R. L. Burgner, J. C. Gislason, P. E. Huffman, K. H. Wyman, R. G. Gibbons, K. W. Kirko, Q. J. Stober, T. W. Fagnan, A. P. Stayman and D. M. Eggers. 1979. Assessment of Reservoir Related Effects of the Skagit River Project on Downstream Fishery Resources of the Skagit River, Washington. Final Report to Seattle City Light. U. of WA., Fish. Res. Ins. FRI-UW-7905. 602 pp.

Hamilton, R. and J. W. Buell. 1976. Effects of Modified hydrology on Campbell River Salmonids. Technical Report Series No. Pac/T-76-20. Canada Department of the Environment, Fisheries and Marine Service. Vancouver, B. C. 156 pp.

Hvisten, N. A. 1985. Mortality of pre-smolt Atlantic salmon, Salmo salar L., and brown trout, Salmo trutta L., caused by fluctuating water levels in the regulated River Nidelva, central Norway. Journal of Fish Biology. 1985:711-8.

Jones and Stokes Associates. 1985. Salmon and Steelhead Fry Trapping and Stranding in Potholes on the Skagit River, 1984. Prepared by Jones and Stokes Associates, Bellevue, WA for Seattle City Department of Lighting, Seattle, WA.

Kelly, J. A. 1980. Potential environmental effects of small-scale hydroelectric development in Oregon. Water Resources Institute, Oregon State University. 51 pp.

Leathe, S. A. and M. D. Enk. 1985. Cumulative Effects of Micro-Hydro Development on the fisheries of the Swan River Drainage, Montana. Final Report. Division of Fish and Wildlife, Bonneville Power Administration. July 1985. 300 p.

McPhee, C. and M. A. Brusven. 1976. The Effect of River Fluctuations Resulting from Hydroelectric Peaking on Selected Aquatic Invertebrates and Fish. September, 1976. Submitted to the Office of Water Research and Technology, US Dept. of Interior. Idaho Water Resources Research Institute, U. of Idaho, Moscow, ID. 46 p.

Monk, C. L. 1989. Factors that Influence Stranding of Juvenile Chinook Salmon and Steelhead Trout. Master's Thesis. University of Washington, Seattle WA. 81 pp.

Mundie, J. H. and D. E. Mounce. 1976. Effects of Changes in Discharge in the Lower Campbell River on the Transport of Food Organisms of Juvenile Salmon. Appendix Report In: Hamilton, R. and J. W. Buell. 1976. Effects of Modified hydrology on Campbell River Salmonids. Techincal Report Series No. Pac/T-76-20. Canada Department of the Environment, Fisheries and Marine Service. Vancouver, B. C. 156 pp.

Neitzel, D.A., C.D. Becker and C.S. Abernathy. 1985. Proceedings of the Symposium on Small Hydropower and Fisheries, May 1-3, 1985, Aurora, Colorado. F. Olson, R. White and R.H. Hamre, Editors. American Fisheries Society.

Nestler, M.N., R.T. Milhous and J.B. Layzer. 1989. Instream Habitat Modeling Techniques. In J. A. Gore and G E. Petts, Eds. Alternatives in Regulative River Management. CRC Press. Baco Raton, Florida. 1989.

Noll, W. T., 1979. Effects of Dewatering of Artificial Redds with and Effects of Dewatering of Artificial Redds with and without Intermittent Sprinkling on the Survival and Growth of Juvenile Spring Chinook. Prepared by the Research and Development Section, Oregon Department of Fish and Wildlife for the US Army Corps of Engineers. 13 pp.

Olson, F. W. 1990. Downramping Regime for Power Operations to Minimize Stranding of Salmon Fry in the Sultan River. Contract report by CH2M Hill (Bellevue, WA.) for Snohomish County PUD 1. 70 pp.

Phillip, R. W. 1969. Effects of an Unusually Low Discharge From Pelton Regulating Reservoir, Deschutes River, on Fish and Other Aquatic Organisms. Special Report 1. Basin Investigation Section, Oregon State Game Commission.

Phinney, L. A., 1974. Further Observations on Juvenile Salmon Stranding in the Skagit River, March 1973. WDF, Olympia, WA. Prog. Rep. 26:34 pp.

Phinney, L. A., 1974b. Report on the 1972 Study of the Effect of River Flow Fluctuations Below Merwin Dam on Downstream Migrant Salmon. WDF. Unpubl. ms. 23 pp.

Phinney, L.A., L. O. Rothfus, J A. R. Hamilton and E. Weiss., 1973. The study of the effect of river flow fluctuations below merwin dam on downstream migrant salmon. In Western Washington Power Dam Review. WDF. Olympia WA. 55 pp.

Prewitt, C. M. and C. Whitmus. 1986. A technique for quantifying effects of daily flow fluctuations on stranding of juvenile salmonids. Instream Flow Chronicle. January 1986. Colorado State University Conference Services. 3 pp.

Reiser, D. W. and R. G. White. 1983. Effects of Complete Redd Dewatering on

Salmonid Egg-Hatching and Development of Juveniles. Trans. Amer. Fish. Soc. 112:532-540.

Rochester, H. Jr., T. Lloyd and M. Farr. 1984. Physical Impacts of Small-Scale Hydroelectric Facilities and Their Effects on Fish and Wildlife. Division of Biological Services, US Fish and Wildlife Service, Dept. of Interior. Wash., D.C. (FWS/OBS-84/19) 192 p.

Sale, M. J. et. al. 1991. Environmental Mitigation at Hydropower Projects. Volume 1. Current Practices for Instream Flow Needs, Dissolved Oxygen, and Fish Passage. Prepared by Oak Ridge National Laboratory (Tennessee) and

Biennial Progress Report: Rogue Basin Fisheries Evaluation Program, Lost Creek Dam Studies. Prepared by Research and Development Section, Oregon Dept of Fish and Wildlife for US Army Corps of Engineers, DACW57-77-C-0007. 33 pp.

Schlosser, I. J. 1982. Trophic structure, reproductive success, and growth rate of fishes in a natural and modified headwater stream. Can. J. Fish. Aquat. Sci. 39:968-978.

Stober, Q. J., S. C. Crumley, D. E. Fast, E. S. Killebrew, R. M. Woodin, G. E. Engman and G. Tutmark. 1980. Effects of Hydroelectric Discharge Fluctuation on salmon and steelhead in the Skagit River, Washington. Final Report for period December 1979 to December 1982. Seattle City Light Contract. U. Washington, Fish. Res. Inst. FRI-UW-8218. 302 pp.

Thompson, J.S. 1970. The Effect of Water Regulation at Gorge Dam on Stranding of Salmon Fry in the Skagit River, 1969-1970. WDF. Olympia, WA. Unpubl. MS. 46 p.

Thuemler, T. F., G. E. Welan, and J. D. Fossum. 1991. Assessment of the Effects on Aquatic Habitat from a Hydroelectric Peaking Project Using the Instream Flow Incremental Methodology. Instream Flow Chronology. Vol. 8(1). Colorado State University.

Trotzky, H. M. and R. W. Gregory. 1974. The effects of water flow manipulation below a hydroelectric power dam on the bottom fauna of the upper Kennebec River, Maine. Transactions of the American Fisheries Society. 103:318-324.

Water Resources Research Institute (WRRI). 1983. The Impact of small scale

Table 1. Monthly tabulation of 11,771 measurements of hourly state for Youngs Creek, a tributary to the Skykomish River in Washington. October 1989 to May 1991. Flow measurements were accurate to the 0.001 foot. It should be noted that this time period had many severe storm events, even by Western Washington standards. Thus, variability in water stage change is probably greater than might be expected in a longer sequence of data collection. Data provided by Beak Consultants, Kirkland, WA.

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEPT	OCT	NOV	DEC	TOTAL
Average Increase	0.86	0.93	0.71	0.61	0.67	0.39	0.36	0.28	1.44	1.26	0.75	0.75	0.80
Average Decrease	-0.53	-0.56	-0.46	-0.34	-0.35	-0.20	-0.21	-0.21	-0.21	-0.65	-0.50	-0.50	-0.47
Number of Increases	438	369	296	250	222	165	132	171	134	225	339	428	3,199
Number of No Changes	332	182	97	92	511	185	331	326	366	134	207	419	3,182
Number of Decreases	718	559	351	382	388	370	281	247	218	535	701	640	5,390
Totals	1,488	1,110	744	724	1,121	720	744	744	718	924	1,247	1,487	11,771
Distribution of Flow Changes by Month in Inches													
change=> 10"		1						1		1	4		7
9" <= change < 10"									1		1	1	3
8" <= change < 9"							1			1	1		3
7" <= change < 8"		1								2	1	1	5
6" <= change < 7"	3	2		1	1					3		1	11
5" <= change < 6"	6	1		1						11	8	5	32
4" <= change < 5"	6	5	1	0	2	2				8	7	15	48
3" <= change < 4"	15	19	5	1	1	5	1	1		10	12	8	78
2" <= change < 3"	26	20	5	13	6	7	1	1	2	22	40	15	158
1" <= change < 2"	49	51	17	27	19	14	4	2	2	50	44	34	313
0.5" <= change < 1"	73	73	65	72	60	39	19	24		48	67	43	583
0.0" <= change < 0.5"	260	196	203	133	133	98	106	142	129	99	154	305	1,958
No change	332	182	97	92	511	185	331	326	366	134	207	419	3,182
0.0" >= change > -0.5"	530	391	266	269	323	297	272	227	208	313	465	491	4,052
-0.5" >= change > -1"	103	106	69	87	51	56	9	19	8	154	128	77	867
-1" >= change > -2"	48	39	8	18	13	12		1	2	42	63	43	289
-2" >= change > -3"	23	13	7	6	1	4				17	18	15	104
-3" >= change > -4"	5	4	1	2		1				7	15	6	41
-4" >= change > -5"	4	2								1	4	3	14
-5" >= change > -6"	4	1									2	2	9
-6" >= change > -7"											3	1	4
-7" >= change > -8"		2								1	3	1	7
-8" >= change > -9"													1
-9" >= change > -10"		1											1
change <= -10	1												1

Table 2. Tabulation of 11,771 measurements of hourly stage changes by flow exceedence. Measurements are for Youngs Creek, a tributary to the Skykomish River in Washington State. October 1989 to May 1991. Flow measurements were accurate to the 0.001 foot. Measurements are weighed by month, such that each month contributes equally to flow exceedence profile. It should be noted that this time period had many severe storm events, even by Western Washington standards. Thus, variability in stage change is probably greater than might by expected in a longer sequence of data collection. Data Provided by Beak Consultants, Kirkland, WA.

Exceedence Percentile	100-90%	90-80%	80-70%	70-60%	60-50%	50-40%	40-30%	30-20%	20-10%	10-0%

Table 3. Tabulation of 17,244 records of hourly river stage changes on the Sauk River (USGS #12189500) by flow exceedence percentiles. Data from October 1, 1989 to September 19, 1991. Note that only one decline in flow in excess of 2 inches per hour occurred below the 90 percent flow exceedence (ie. the river flow that is exceeded 90 percent

Exceedence Percentiles	100-90%	90-80%	80-70%	70-60%	60-50%	50-40%	40-30%	30-20%	20-10%	10-0%	Total
Flow Description	Very Low		Low			Medium		High		Flood	
change => 10"								1		3	4
9" <= change < 10"							1		1	1	3
8" <= change < 9"								1		5	6
7" <= change < 8"										6	6
6" <= change < 7"				1					1	9	11
5" <= change < 6"				1		1		4	2	9	17
4" <= change < 5"				1			2		3	17	23
3" <= change < 4"				1	2	3	2	1	5	40	55
2" <= change < 3"	4	2	2	1	5	3	7	3	9	51	87
1" <= change < 2"	5	6	5	7	15	13	20	42	35	131	279
0.5" <= change < 1"	8	14	19	35	40	45	57	69	119	114	520
0.0" <= change < 0.5"	330	228	259	291	330	352	362	323	344	232	3,051
No change	738	1,003	889	706	481	394	305	293	221	78	5,108
0.0" > change > -0.5"	637	469	540	670	837	905	957	946	900	527	7,388
-0.5" >= change > -1"	1	2	10	8	14	8	10	41	64	250	408
-1" >= change > -2"				2				1	20	155	187
-2" >= change > -3"							1			54	55
-3" >= change > -4"										28	28
-4" >= change > -5"										11	11
-5" >= change > -6"										2	2

Table 4. Tabulation of 17,244 records (including 118 no data records) of hourly changes in stage on the Skagit River at Marblemount (USGS #12181000) by flow exceedence percentiles. Data from October 1, 1989 to September 19, 1991. Flow is regulated by three upstream dams. The flow exceedence percentiles are extrapolated from the Sauk River flow exceedence [illegible]

2 inches per hour occurred below the 90 percent flow exceedence.

Exceedence Percentiles	100-90%	90-80%	80-70%	70-60%	60-50%	50-40%	40-30%	30-20%	20-10%	10-0%	Total
Flow Description	Very Low		Low			Medium		High		Flood	
change => 10"										6	6
9" <= change < 10"								2	1	2	5
8" <= change < 9"						1	1			2	4
7" <= change < 8"						2		2	2	7	13
6" <= change < 7"					2	3	4	1		7	17

TABLE 5. Ramping Range, Maximum Ramping Rate, Ramp Duration, and Lag Time recorded from four gages on the Skagit River as a result of an experimental fluctuation event on March 19, 1982. Data was available in hourly intervals. Data provided by Mr. Thomas Higgins, U.S. Geological Survey, Tacoma.

Gage Site (River Mile)	Ramping Range (Feet)	Maximum Ramping Rate (Feet/Hour)	Duration (Hours)	Lag Time (Hours)
93.7	1.6	.9	2	0
85.8	1.2	.7	4	1
78.7	0.8	.4	5	2
54.1	0.7	.2	5	7

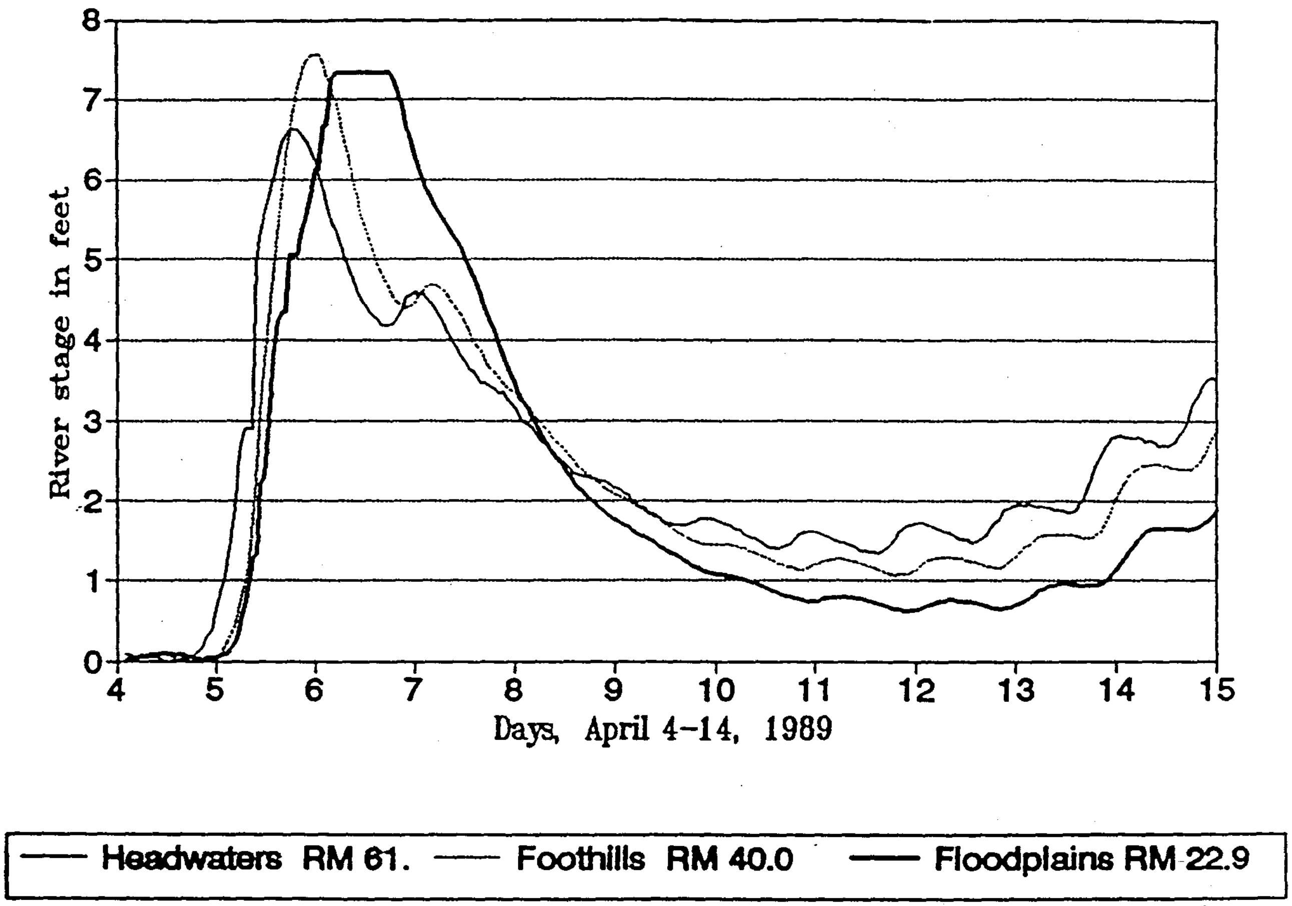


Figure 1. River Stages From Three Snoqualmie River USGS Gages, April 4 to April 14, 1989. The headwater gage is #12143400, the foothill gage is #12144500, and the flood plains gage is #12149000. All three gauges are in the Snoqualmie River Basin. The data was recorded every 15 minutes. All plotted values were standardized by subtracting the minimum recorded value during the April 4 to April 14 time period from each site from all the other values recorded from the same site. In addition, values from the "Headwater" gauge were scaled by a factor of two to produce a plot of similar range to other two sites. Data from the US Geological Survey ADAPS database, Tacoma, WA.

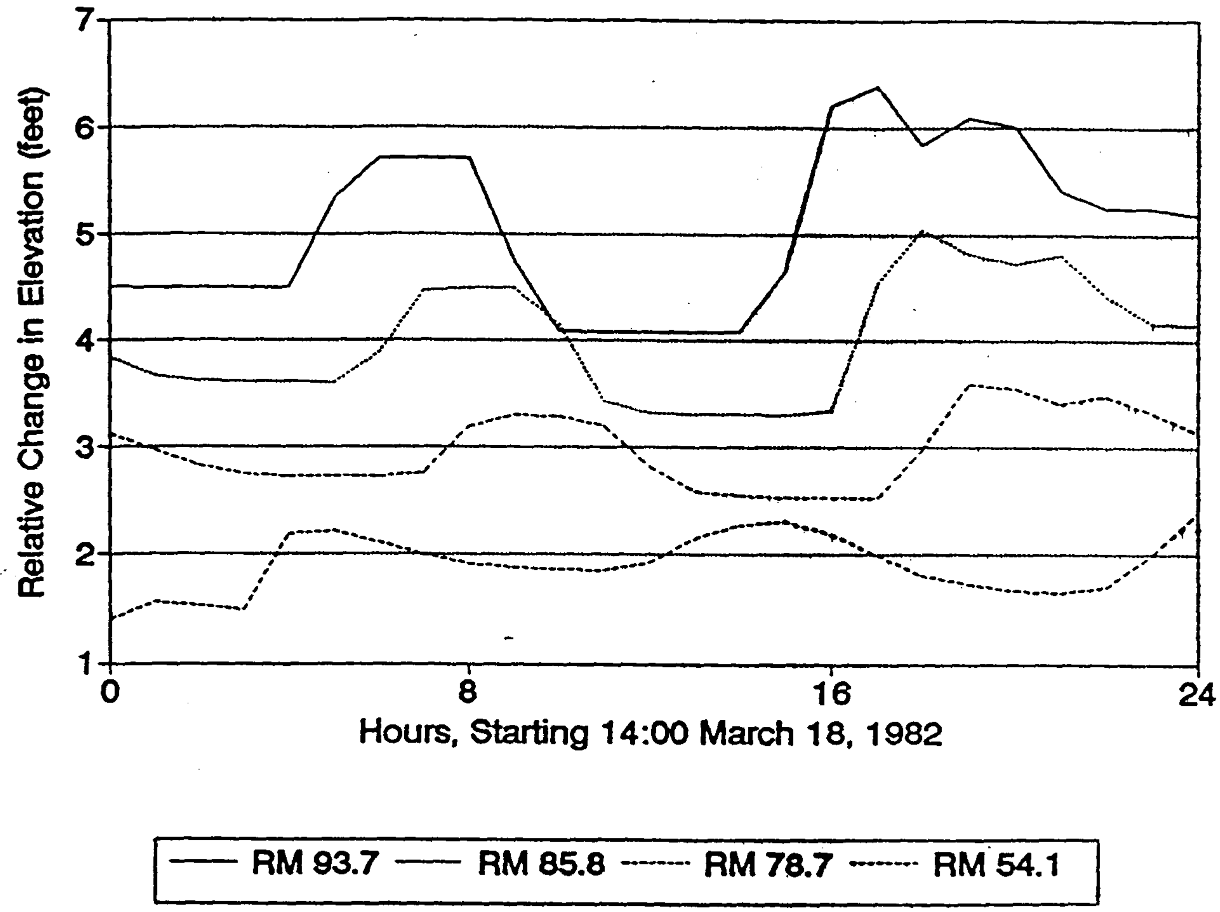


Figure 2. Hourly River Stage Recordings From Four Gages on the Skagit River, March 19, 1982. The fluctuation, as shown by the "hump" that progresses downstream over time, is a result of an experimental discharge from the Newhalem Powerhouse at RM 94.3 for the purpose of evaluating stranding. The horizontal grids represent one foot of water surface change. The plots of each gauge are centered on separate grid lines going downstream from top to bottom. The plots are separated for purpose of interpreting water surface changes, and do not reflect actual elevation changes between gages. Data provided by Mr. Thomas Higgins, U.S. Geological Survey, Tacoma, WA. The gauge numbers in downstream sequence are 12178000, 12179000, 12181000, and 12194000.

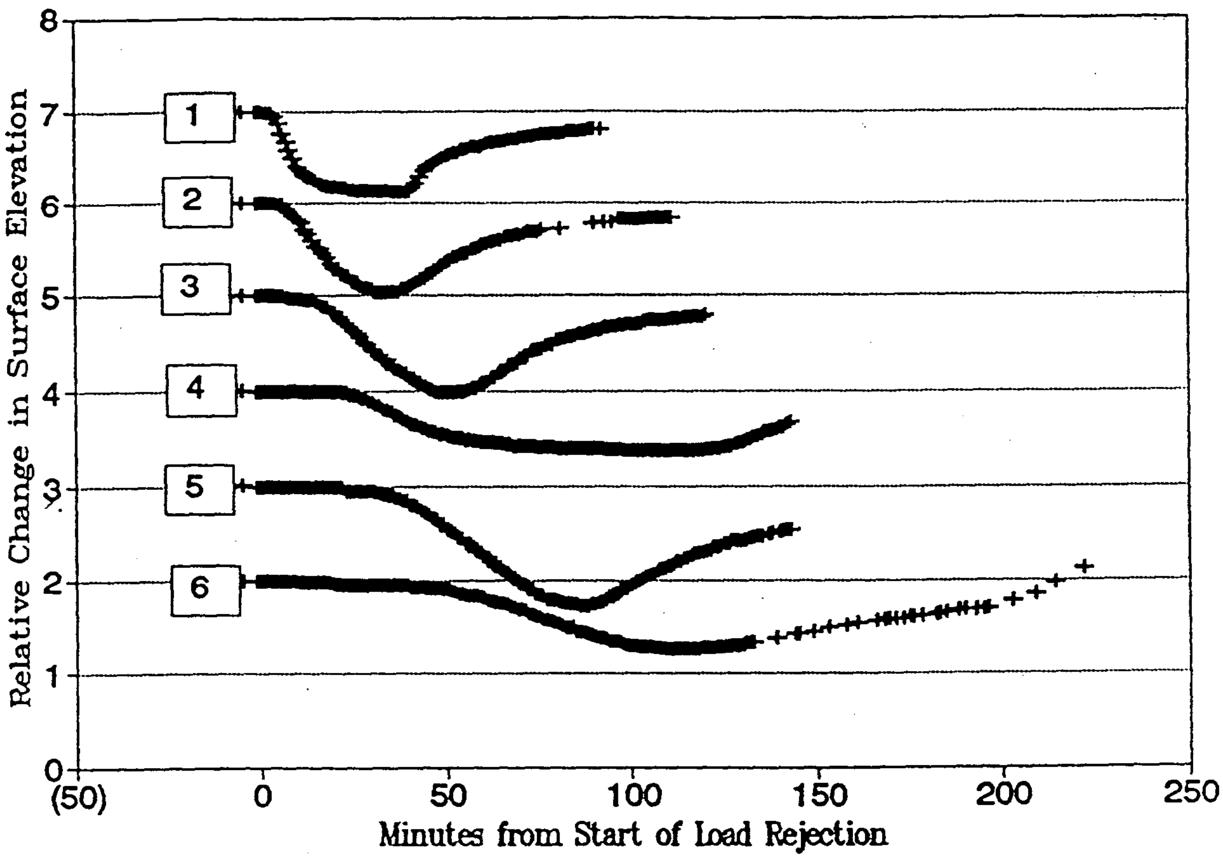
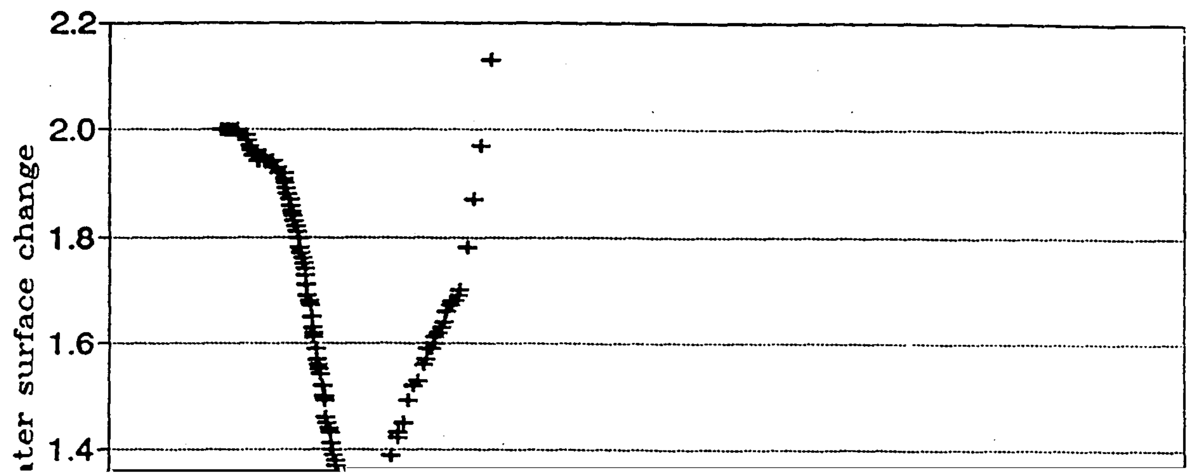


Figure 3. River Stage Recordings From Six Sites Below the Snoqualmie Falls Second Powerhouse. The fluctuation was staged to evaluate ramping and stranding during load rejection under low flow conditions. The horizontal grids represent one foot of water surface change. The plots for each gage are standardized to the first data record and plotted on separate grid lines going downstream from top to bottom. The plots are separated for purpose of interpreting water surface changes and do not reflect actual elevation changes between gages. The sites progressing from top to bottom are located at 0.4, 0.7, 1.4, 1.7, 2.1 and 4.6 miles below the powerhouse. Data was provided by Cary Feldman, Puget Power, Bellevue, WA.


2.2
2.0
1.8
1.6
1.4
ter surface change

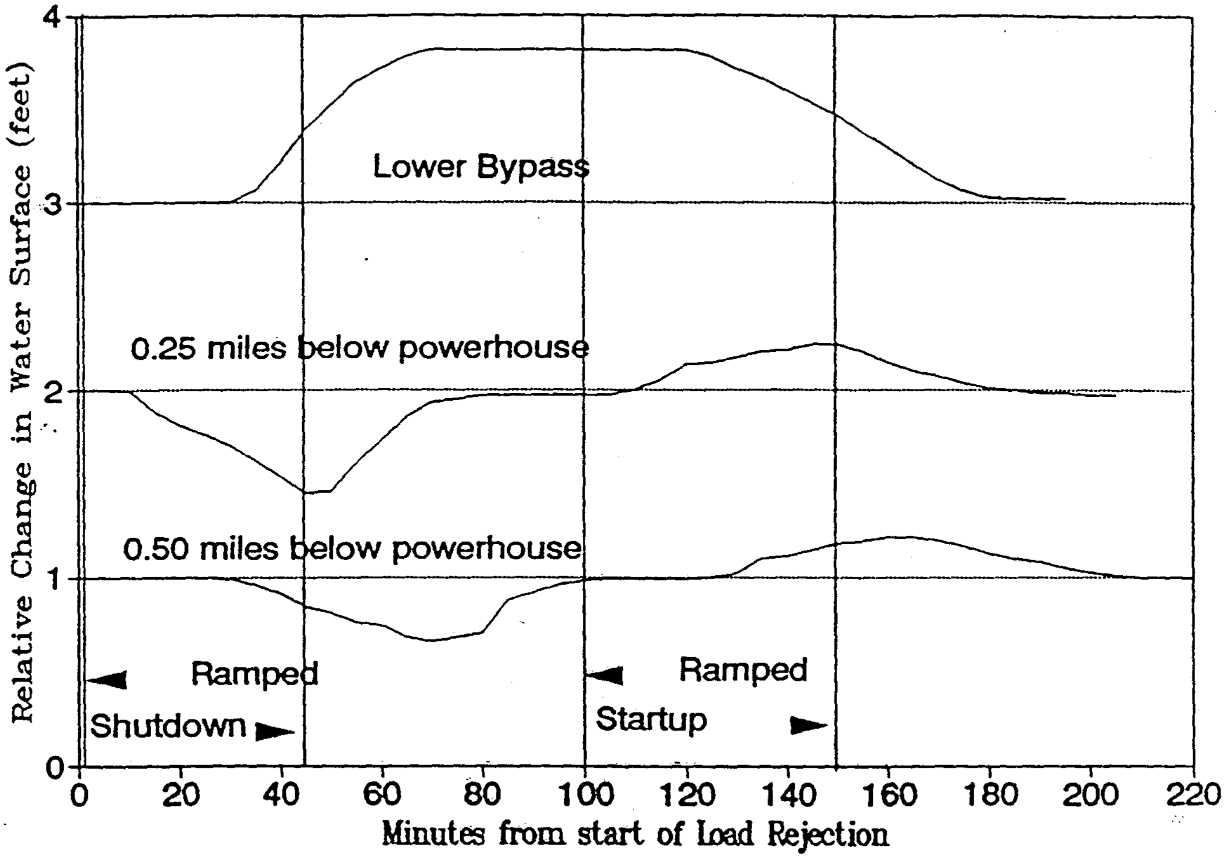


Figure 5. Flow Fluctuations at a Run-of-the-River Facility. This plots the stage change at the Twin Falls Project on the SF Snoqualmie River in a test where the discharge is ramped down over a 45-minute period and then ramped up over a 50- [illegible]

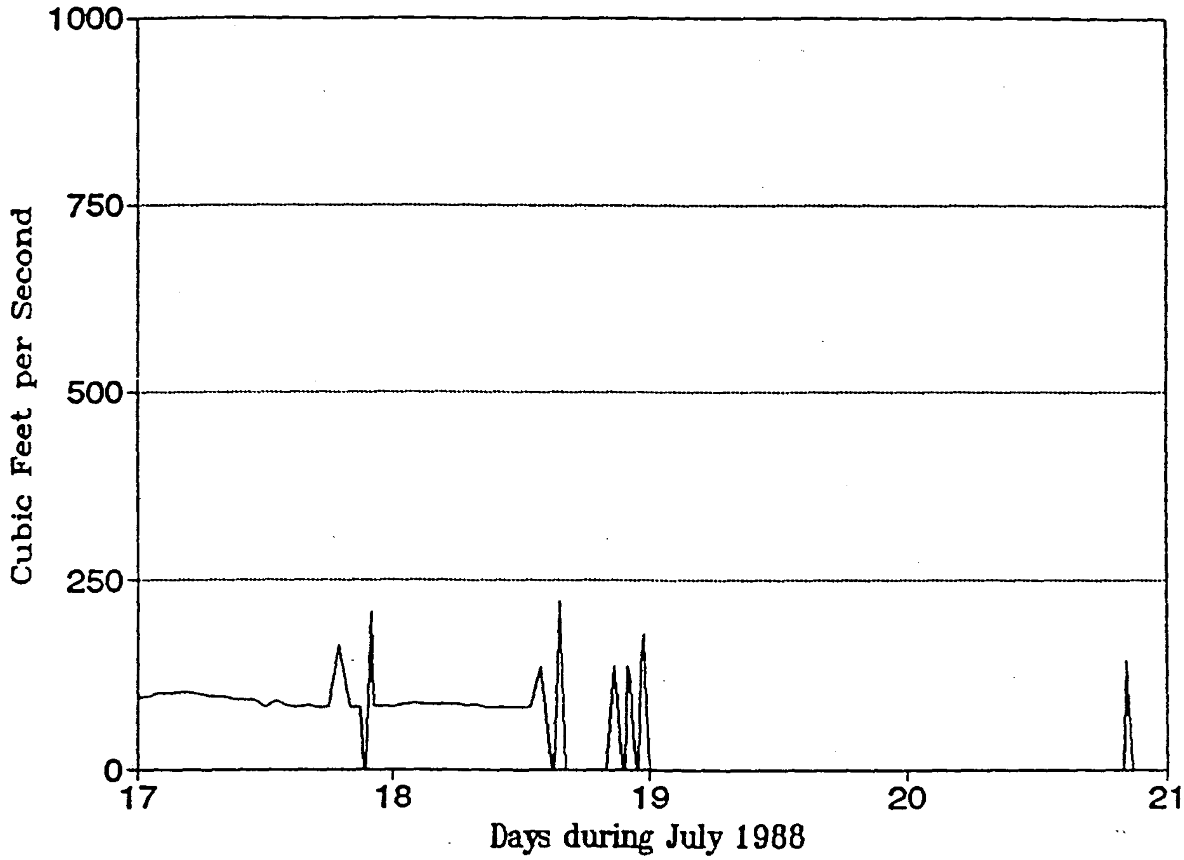
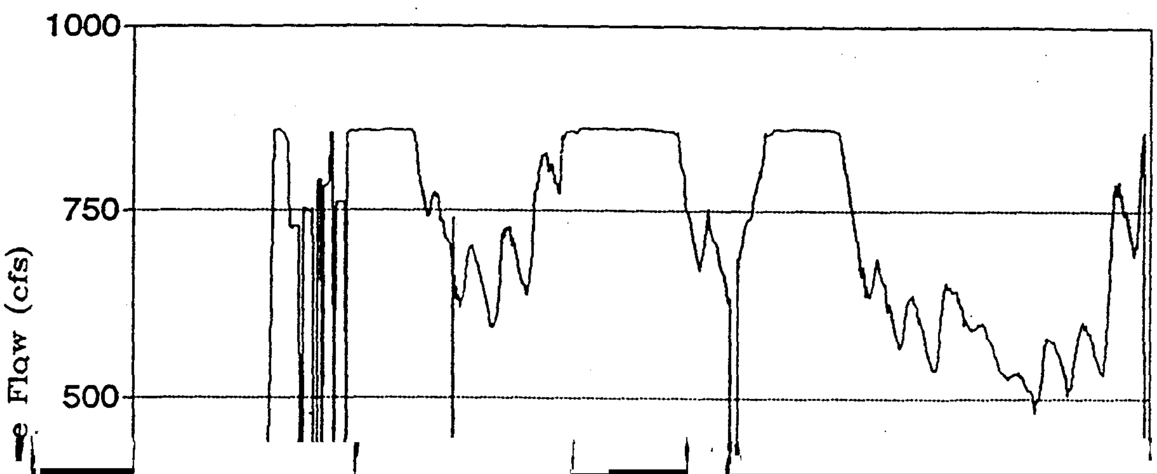


Figure 6. Weeks Falls Turbine Flows During July 17 through 21, 1988. An example of cycling and forebay surging when river flow is at or near the minimum operating flows for the project. The combination of these two problems cause substantial flow fluctuations below the powerhouse at low flows when the aquatic community is most vulnerable. (Data from Hosey & Associates, Bellevue, WA; currently Harza NW, Inc.)


1000
750
500
Flow (cfs)